DESIGNING SUSTAINABLE COVERS FOR URANIUM MILL TAILINGS

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ABSTRACT

The U.S. Department of Energy in Grand Junction, Colorado, combines three tools to design and evaluate the performance of engineered covers for uranium mill tailings: field monitoring, modeling, and natural analog studies. This paper presents lessons learned from monitoring existing low-permeability covers, tests of alternative covers intended to accommodate long-term environmental change, and the use of natural analog studies in combination with monitoring and modeling to project the long-term performance of both low-permeability covers and alternative covers. The saturated hydraulic conductivity of conventional, low-permeability covers can be one to several orders of magnitude greater than designed because of biological intrusion and soil development in compacted soil layers. Lysimeter studies show that alternative cover designs that rely on the water storage capacity of a thick soil sponge to retain precipitation while plants are dormant, and evapotranspiration to dry the sponge during the growing season, can limit infiltration of tailings. Clues about possible long-term changes in the environmental setting of engineered covers can be gleaned from evaluations of past changes in analogous settings. Data from natural analog sites can be input to probabilistic models to estimate reasonable ranges of future performance.

INTRODUCTION

The U.S. Department of Energy (DOE) Office of Legacy Management is responsible for long-term stewardship of former uranium ore processing and mill tailings sites in all regions of the country (www.gjo.doe.gov/programs/ltsm/). Final remedies at most sites include engineered cover systems designed to contain tailings contaminants and limit human health and ecological risks for 200 to 1000 years (U.S. Environmental Protection Agency, 1983)—an unprecedented engineering challenge. Notwithstanding this longevity requirement, existing cover design and performance evaluation guidelines (U.S. Environmental Protection Agency, 1989; U.S. Department of Energy, 1989) are prescriptive in nature and fail to consider influences of inevitable changes in the environmental setting.

In contrast, the DOE Environmental Sciences Laboratory in Grand Junction, Colorado, combines three tools to design and project the long-term performance of engineered covers for uranium mill tailings: field monitoring, modeling, and natural analog studies. This paper presents examples and lessons learned from (1) monitoring existing covers, (2) designing alternative covers that accommodate long-term environmental change, and (3) using natural analog studies in combination with monitoring and modeling to project the long-term performance of both existing and alternative covers.

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MONITORING EXISTING COVERS

Many DOE Office of Legacy Management sites have disposal cells designed and constructed under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA). The design philosophy for UMTRCA covers evolved in response to regulatory changes and applications of lessons learned (Waugh et al., 2001). Before groundwater quality standards for UMTRCA sites were promulgated, the design process focused on radon attenuation and a 1,000-year longevity standard. The early designs consisted basically of three layers (U.S. Department of Energy, 1989a): (1) a compacted soil layer (CSL) or radon barrier overlying the tailings, (2) a surface layer of rock for erosion protection, and (3) sandwiched in between, a lateral drainage layer consisting of coarse sand and gravel. The CSLs in these designs were later advocated as low-permeability barriers to water movement into the tailings (U.S. Department of Energy, 1989a).

Plants began growing on the rock covers within a few years after construction (U.S. Department of Energy, 1992). Emergence of vegetation should have been anticipated. Surface layers of rock reduce evaporation (Groenevelt et al., 1989), increase soil water storage (Kemper et al., 1994), and consequently create habitat for deep-rooted plants.

A key issue is whether deep-rooted plants will increase or decrease the likelihood of contaminant discharge from the disposal cell. This issue can be argued two ways. Decaying plant roots may create conduits through which water and gases readily pass, thus potentially increasing permeability and downward flux. Conversely, extraction of soil water from the cover by plants (transpiration) may significantly decrease flux. Even in humid climates, where precipitation exceeds potential evapotranspiration, water extraction by plants may account for more than half the soil water loss from disposal cell covers (Melchior et al., 1994). Woody vegetation has also been shown to improve the stability of riprap-armored slopes, although the complexity of vegetation and rock-slope interactions has hampered quatification (Morgan and Rickson, 1995).

Problems with deep-rooted plants may counteract the potential benefits. Plants can root through soil covers into underlying waste material, disseminating contaminants in aboveground tissues. Plants rooted in uranium mill tailings may contain elevated levels of U, Mo, Se, 226Ra, 230Th, and 210Po (Clulow et al., 1991; Dreesen and Williams, 1982; Hosner et al., 1992; Lapham et al., 1989; Markose et al., 1993). Radon-222 can be transported into the atmosphere as plant roots extract water from tailings (Lewis and MacDonell, 1990; Morris and Fraley, 1989). Roots may also alter waste chemistry, potentially mobilizing contaminants (Cataldo et al., 1987).

Root intrusion can also physically degrade covers. Evidence has increased suggesting that covers with compacted soil layers are vulnerable to desiccation and cracking from wet-dry cycles, freeze-thaw cycles, and biointrusion (Melchior et al., 1994, Kim and Daniel, 1992). Macropores left by decomposing plant roots can act as channels for water and gases to rapidly bypass the soil mass in compacted soil layers. Plant roots also tend to concentrate in and extract water from compacted clay layers, causing desiccation and cracking. This can occur even when overlying soils are nearly saturated (Hakonson, 1986), indicating that the rate of water extraction by plants may exceed the rehydration rate of the compacted clay. In addition, roots may clog lateral drainage layers (U.S Department of Energy, 1992), potentially increasing rates of infiltration through the underlying compacted soil.

Results of performance evaluations of early, rock-armored, low-permeability covers at an arid site, Shiprock, New Mexico, and a humid site, Burrell, Pennsylvania, are summarized below.

Shiprock, New Mexico

The Shiprock, New Mexico, disposal cell was constructed in 1986 before the U.S. Environmental Protection Agency (EPA) proposed ground water quality standards for uranium mill tailings sites. The cover design used at Shiprock consists of three layers (Figure 1): a 198-cm silt loam CSL to control radon releases, a 15-cm sand drainage/bedding layer overlying the CSL, and a 30-cm rock armor layer sized to prevent erosion. On the basis of laboratory tests, the Shiprock CSL was thought to have a saturated hydraulic conductivity (Ksat) between 6.4 x 10-8 and 2.3 x 10-6 cm /s (U.S. Department of Energy, 1989b). DOE became concerned in the years after construction that vegetation observed growing on the cover could compromise the low permeability of the CSL. Potentially deep-rooted species included tamarisk, rubber rabbitbrush, gray horsebrush, and Russian thistle.

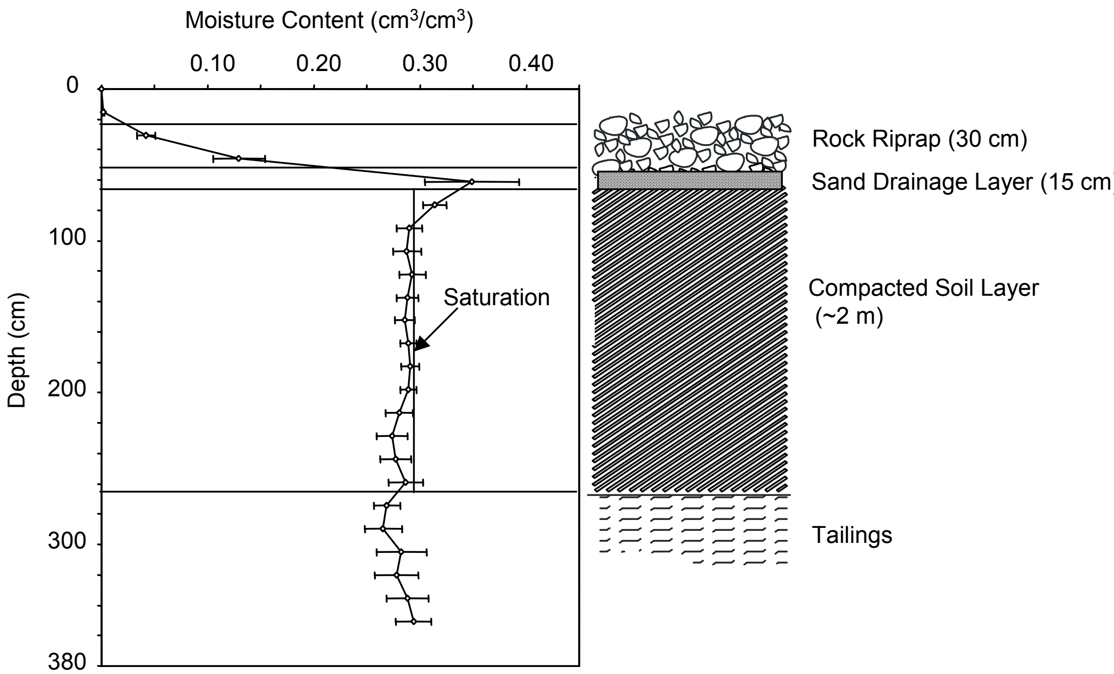

Figure 1. Cover design for the Shiprock, New Mexico, uranium mill tailings disposal cell, mean (± 2SEM) volumetric soil moisture profile monitored monthly from June 1999 to September 2000, and volumetric moisture content of the compacted soil layer at saturation.

Results of soil moisture monitoring and in situ measurements of Ksat indicate that the cover may not be performing as anticipated (Glenn and Waugh, 2001). Soil moisture profiles through the CSL and into underlying tailings were measured monthly between June 1999 and September 2000 using a neutron hydroprobe (Gardner, 1986) at four locations in the cover. The moisture content of the CSL (mean = 28.8 percent by volume, SEM = 0.6) and the porosity of the CSL (27.1 percent, SEM = 1.7) were statistically the same; the CSL was essentially 100-percent saturated (Figure 1).

The in situ Ksat of the CSL was measured at six locations in 1998 using air-entry permeameters designed and manufactured by Daniel B. Stephens and Associates, Inc. (Stephens et al. 1988). The AEP, based on a design by Bouwer (1966), consists of a round, 30-cm-deep permeameter ring, air-tight cover, standpipe, graduated water reservoir, and vacuum gauge. The vacuum gauge measurement is used to calculate the air-entry or bubbling pressure of the soil. Three AEP measurements were made in pits excavated where tamarisk, rubber rabbitbrush, and Russian thistle rooted into the CSL, and in adjacent pits where plant root intrusion was not observed. Results were highly variable with a mean = 4.4 x 10-5 cm/s that was significantly greater than the laboratory test mean. CSL Ksat values were actually lower in locations where roots penetrated the CSL than in locations with no observed root intrusion.

If the CSL remains continuously saturated, as neutron hydroprobe data indicate, then the passage of water through the CSL and into the tailings would be greatly influenced by the Ksat. Under saturated conditions, the hydraulic gradient is approximately 1 and water flux through the cover can be estimated using Darcy's law. Given near-saturation of the CSL and tailings, and the high values for the CSL Ksat, it would be prudent to further evaluate water flux through the disposal cell to assure that the source of groundwater contamination is contained.

Burrell, Pennsylvania

The effects of root intrusion on the performance of the uranium mill tailings disposal cell at Burrell, Pennsylvania, were also evaluated (Waugh and Smith, 1997). As with Shiprock, the intended design life is 200 to 1,000 years. Annual precipitation at Burrell averages greater than 100 cm/yr.

From the bottom up, the Burrell cover consists of a 90-cm CSL overlying residual radioactive materials (RMM), a 30-cm sand and gravel drainage layer, and a 30-cm rock riprap layer. (See Waugh et al. [1999] for soil physical and hydraulic property data.) Within 3 years after construction, a diverse community of woody plants had established on the rock cover of the disposal cell, including sycamore, box elder, black locust, tree-of-heaven, and Japanese knotweed, an exotic perennial with a woody base. Within 10 years Japanese knotweed had rooted through the rock layer and the underlying CSL.

Air-entry permeameters (Stephens et al. 1988) were also used at Burrell to measure the in situ Ksat of the CSL. The Ksat averaged 3.0 x 10–5 cm/s at locations where Japanese knotweed roots penetrated the CSL compared to 2.9 x 10–7 cm/s at locations where there were no plants. The weighted-average Ksat for the 6-acre cover, calculated using the community leaf area index (LAI) for Japanese knotweed, was 4.4 x 10–6 cm/s. Plant community LAI was estimated with an LAI-2000 Plant Canopy Analyzer (Wells and Norman, 1991; LI-COR, Inc., 1992). At a nearby site with a subsoil consisting of the same type of material as used for the CSL, the Ksat averaged 1.3 x 10–4 cm/s. Earthworm holes, root channels, and soil structural planes all contributed to macropore flow of water in the subsoil. This nearby site was considered to be a reasonable analog of the long-term condition of the Burrell disposal cell cover.

ALTERNATIVE COVER DESIGN

Lessons learned from monitoring early UMTRCA covers contributed to design improvements. The low-permeability covers attempt to resist natural processes, rather than work with them, and will likely require increasing levels of maintenance or retrofitting in the future (Clarke et al. in press). DOE and the U.S. Environmental Protection Agency (EPA), Region 8, collaborated on an alternative design for a uranium mill tailings disposal cell at the Monticello, Utah, Superfund Site (Berwick et al., 2000). The goal at Monticello was to design an engineered cover system that enhances beneficial natural processes to help make long-term containment possible (Waugh and Richardson, 1997).

At semiarid sites such as Monticello, relatively low precipitation (P), high potential evapotranspiration (PET), and thick unsaturated soils seem to favor long-term hydrologic isolation of buried waste (Winograd, 1981; Reith and Thompson, 1992). But simple P/PET relationships inadequately predict recharge that can approach 60% of precipitation in arid regions where coarse-textured soils have been denuded of vegetation (Gee and Tyler, 1994). At arid and semiarid sites, recharge can be minimized if disposal cells are covered with thick, fine-textured soil layers that store precipitation in the root zone where evapotranspiration (ET) seasonally removes it (Anderson et al., 1993; Link et al., 1994; Ward and

Gee, 1997). Capillary barriers consisting of coarse-textured sand and gravel placed below this soil "sponge" layer can enhance water storage and limit unsaturated flow (Stormont and Anderson, 1998; Khire et al. 2000). To be accepted by regulators, end users must demonstrate that the water balance of these alternative ET cover designs is at least equivalent to conventional designs (U.S. Environmental Protection Agency, 2003).

Monticello Cover Design

The Monticello alternative cover design (Figure 2) is fundamentally an ET cover with a capillary barrier. The design relies on the water-storage capacity of a 163-cm fine-textured soil sponge layer overlying a 38-cm sand capillary barrier layer to retain precipitation until it is seasonally removed by vegetation. Drainage should occur only if water accumulation at the sponge/sand layer interface approaches saturation and tensions decrease sufficiently for water to enter the larger pores of the sand layer. Hydraulic performance can be evaluated as the probability that, over time, ET is sufficient to prevent water accumulation in the soil sponge from exceeding the storage capacity.

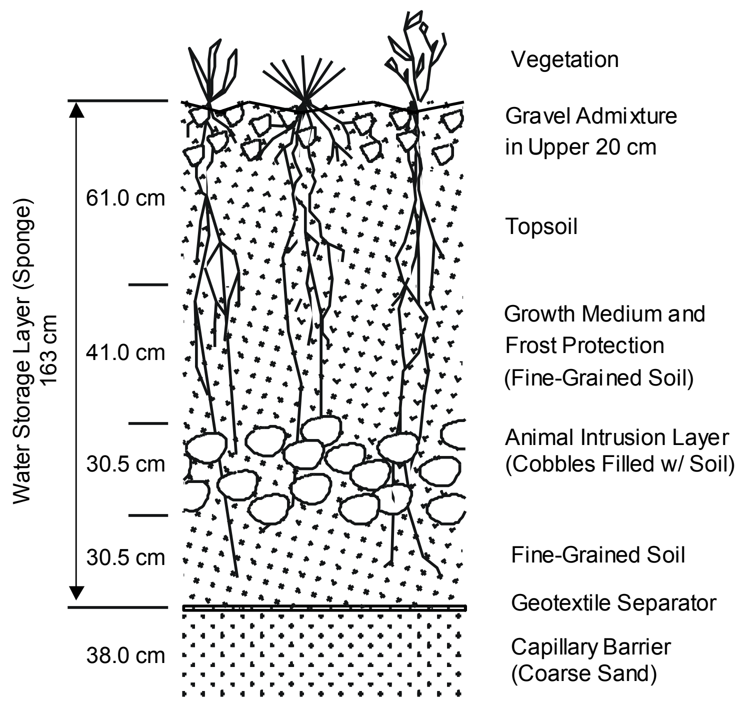

Figure 2. Alternative cover design tested in caisson lysimeters and constructed on a uranium mill tailings disposal cell at the Monticello Superfund Site.

Other components of the Monticello design either facilitated construction or were included to enhance long-term performance. A geotextile fabric maintains the fine-grained soil/coarse sand layer discontinuity during construction and until soil aggregation occurs by natural pedogenic processes (Bjornstad and Teel, 1993). The combination of vegetation and gravel admixture controls erosion. Vegetation and organic litter disperse raindrop energy, shield underlying fine soils, increase infiltration, reduce water flow and surface wind velocity, bind soil particles, and filter sediment from runoff (Wischmeier and Smith, 1978). Gravel mixed into the surface helps control erosion when vegetation is sparse (following construction, fires, drought, etc.), mimicking conditions that lead to the formation of gravel pavements. The gravel admixture can control both wind and water erosion (Ligotke, 1994; Finely et al., 1985) and, functioning as a mulch, can enhance seedling emergence and plant growth (Waugh et al. 1994).

The Monticello design includes deterrents for biointrusion and other attributes for plant growth. The soil sponge thickness is the primary biointrusion deterrent. Water retention in the soil sponge creates habitat for relatively shallow-rooted plants, and the thickness of the sponge exceeds the depth of most burrowing vertebrates in the Monticello area. A layer of cobble-size rock 30.5 cm above the capillary barrier is an added deterrent should deeper burrowers, such as prairie dogs, move into the area in response to climate change. Fine-textured sponge soil fills the interstices of the rock layer, preventing it from behaving like a second capillary barrier. The topsoil layer, obtained from the root zone of the borrow area, has physical and hydraulic properties similar to the rest of the soil sponge, but also contains available nutrients, propagules, and microorganisms (e.g., mycorrhizae) needed for the establishment of a sustainable plant community.

Caisson Lysimeter Installation

Weighing and drainage lysimeters offer the most direct and reliable means for evaluating soil-water balance of alternative cover designs (Gee and Hillel, 1988). Lysimeters have been used for several years to test the hydrologic performance of waste landfill cover designs (Nyhan et al., 1990; Sachschewsky et al., 1995; Roesler et al., 2002). Two large drainage lysimeters were installed to evaluate the range of as-built conditions in the actual Monticello alternative cover (Waugh et al., 2004) (Figure 3).

Lysimeter 1 closely matches the materials and compaction as built during the latter stages of construction. Lysimeter 2 mimics less desirable materials and compaction as built during the early stages of construction. The sponge layer consists of loam topsoil compacted to 1.45 g/cm2 in Lysimeter 1, and of clay loam subsoil compacted to 1.65 g/cm2 in Lysimeter 2. Lysimeters were installed by excavating a pit using a track hoe. Corrugated steel culverts, 3.05 m in diameter by 2.75 m in depth, form the walls of the lysimeters. Access to instrumentation is through an adjacent caisson, 1.52 m in diameter by 3.66 m in depth. Culverts were lined with 40-mil high-density polyethylene (HDPE), filled with water, covered with plastic, and leak tested using a manometer. HDPE tubes, welded to drainage holes cut into the lower end of the HDPE floor liner, were inserted through ports into the access caisson. Soil layers were installed by marking soil lift heights on the interior walls, hauling and dumping stockpiled materials into the lysimeters, spreading and wetting lift materials, and then tamping lifts to achieve soil bulk-density specifications. Bulk density was measured with a nuclear density gauge (Troxler Inc.).

Plant Establishment

Revegetation goals for ET covers include plants that (1) are well-adapted to the engineered soil habitat, (2) are capable of high transpiration rates, (3) limit soil erosion, and (4) are structurally and functionally resilient (Waugh and VanReyper, 2002). Diverse mixtures of native and naturalized plants are thought to maximize water removal and remain more resilient given variable and unpredictable changes in the environment resulting from pathogen and pest outbreaks, disturbances (overgrazing, fire, etc.), and climatic fluctuations. In contrast, the exotic grass plantings common on engineered covers are genetically and structurally rigid, are more vulnerable to disturbance or eradication by single factors, and will require continual maintenance.

Revegetation of the Monticello lysimeters matched the specifications and methods used for the adjacent tailings disposal cell (Kastens and Waugh, 2002). Lysimeters were seeded in September 2000 with a mixture of grasses, forbs, and shrubs in an attempt to mimic the potential natural vegetation of the borrow soils and local climate (Table 1).

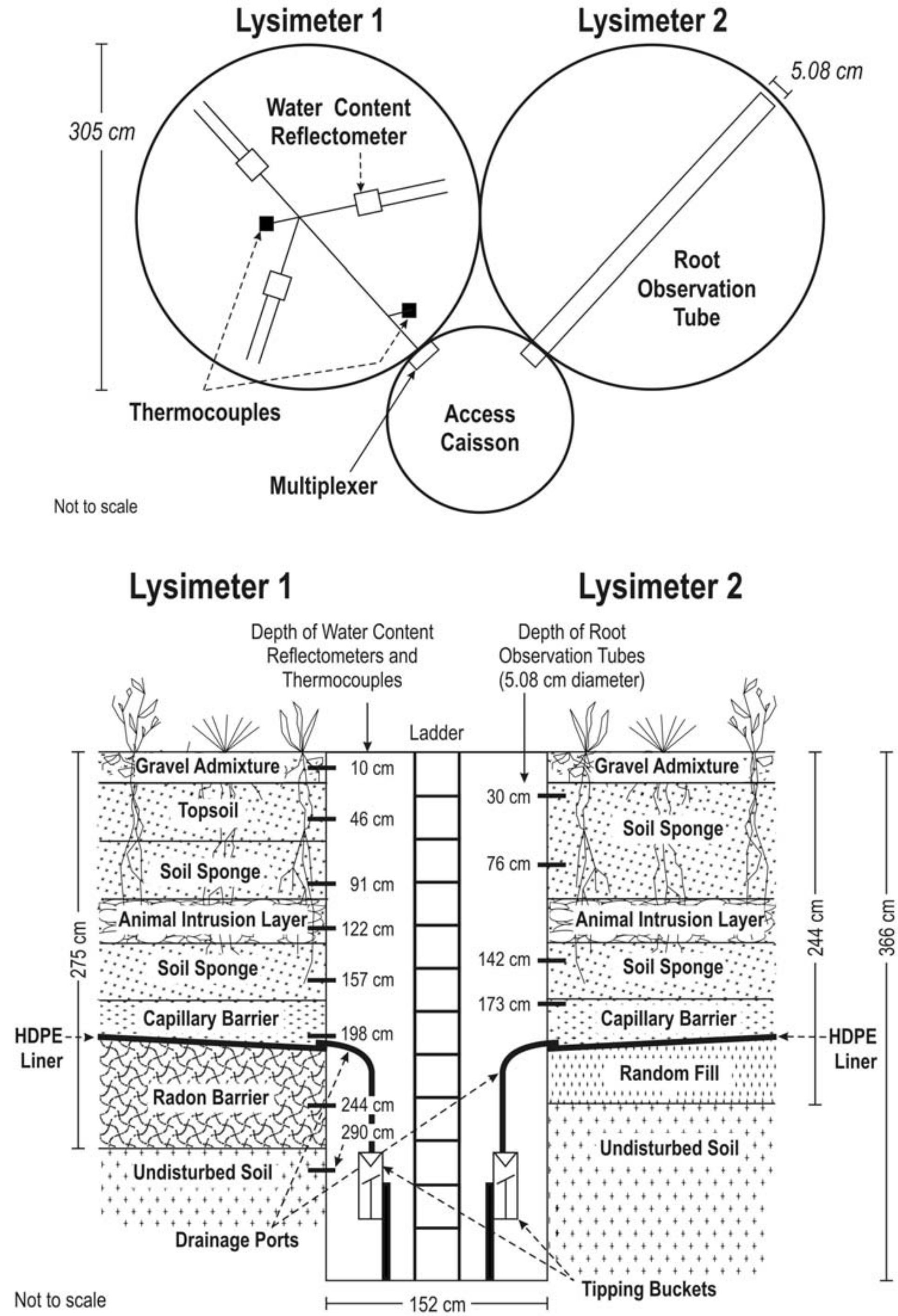

Figure 3. Plan view (top) and cross section (bottom) of instrumentation in the lysimeter and access caissons. Water Content Reflectometers, thermocouples, and root observations tubes, shown separately for purposes of illustrating layouts and depths, were all installed in both lysimeters.

Table 1. Species and seeding rates as planted on the Monticello cover.

Scientific Name	Common Name	PLS/Acre[a]
SHRUBS		
Ericameria nauseosa	Rubber rabbitbrush	1.5
Purshia tridentata	Antelope bitterbrush	1.0
Artemisia tridentata var. vaseyana	Mountain big sagebrushb	0.5
Artemisia tridentata var tridentata	Basin big sagebrush	0.1
Artemisia tridentata var. wyomingensis	Wyoming big sagebrush	0.05
FORBS		
Linum perenne	Blue flax[b]	2.0
Astragalus cicer	Cicer milkvetch[e]	1.6
Sphaeralcea coccinea	Scarlet globemallow[d]	0.5
Sphaeralcea grossulariifolia	Gooseberryleaf	0.5
Erigeron speciosus	Aspen fleabane	0.15
Achillea millefolium	Common yarrow	0.12
Machaeranthera tanacetifolia	Tanseyleaf tansyaster	0.05
GRASSES		
Bromus marginatus	Mountain brome[b]	4.0
Elymus lanceolatus	Streambank wheatgrass	3.0
Pascopyrum smithii	Western wheatgrass[b]	3.0
Stipa comata	Needle-and-thread grass	2.0
Achnatherum hymenoides	Indian ricegrass	2.0
Bouteloua gracilis	Blue grama[d]	1.0
Pleuraphis jamesii	Galleta	1.0

[a]PLS/acre = pure live seed per acre.
[b]Plants seeded and transplanted onto small lysimeters.
[c]Annual or biennial.
[d]Warm season (C4) species.
[e]Not native.

Monitoring Methods, Results, and Discussion

Evaluating the performance of the Monticello cover required a careful analysis of climate, soil hydrology, and plant ecology. Lysimeters enable us to evaluate performance of the cover as a system—an integrated whole—over diurnal, seasonal, and yearly time scales. Our monitoring instrumentation and methods focused on the components of the soil-water balance (precipitation, changes in water storage, drainage, and evapotranspiration) and on plant community composition and relative abundance.

Soil Water Balance

The caisson lysimeter soil surfaces are isolated from runoff and runon, thus ET was estimated using a simplified water balance equation:

$$ET = P - D - \Delta S,$$

where ET, P (precipitation), and ΔS (soil water storage changes) are recorded as mm of water. Precipitation, drainage, and water storage changes were monitored, and actual ET was estimated by difference.

Total annual precipitation, measured with a CSI weather station (Campbell Scientific, Inc., Logan, Utah) has been less than the 30-yr average (39 cm) since the lysimeters were planted in 2000. The 2002 growing season was particularly dry, with winter and spring precipitation about 50% and 15% of normal, respectively. Precipitation was only 57% of normal between November 2000 and June 2002, the critical period for plant establishment.

Soil moisture and water storage were monitored with CS-615 water content reflectometers (WCRs) manufactured by CSI. Drainage was monitored with tipping bucket rain gauges. Drainage did not exceed 0.1 mm/yr, well below the EPA target of <3.0 mm/yr. The only drainage occurred in spring 2000. The lysimeters were not planted until 2000 to allow water storage to build to the maximum limit for each soil type. No measurable drainage occurred during the dry years while vegetation was maturing.

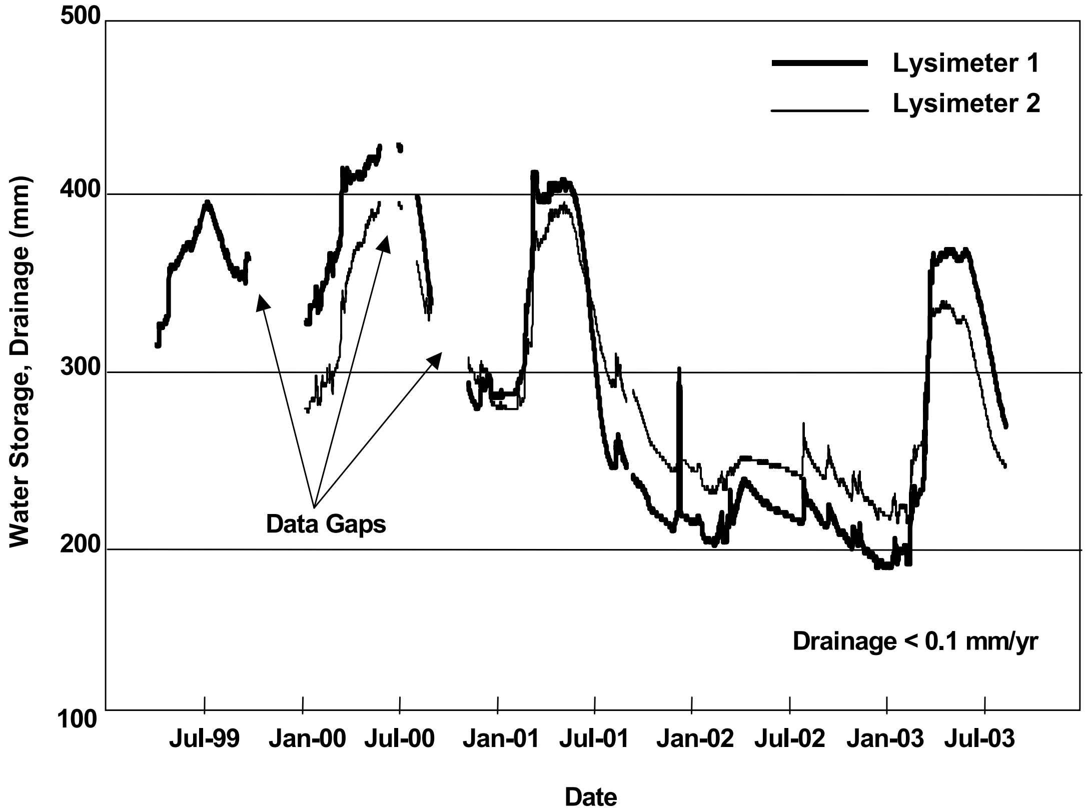

Figure 4. Soil-water storage time series in Lysimeter 1 (less compacted loam soil sponge) and Lysimeter 2 (more compacted clay loam soil sponge) between July 1999 and August 2003.

Time series of water storage changes show conspicuous seasonal variability and an overall drying trend (Figure 4). In both lysimeters, seasonal high and low water storage occurred in mid-to-late spring and mid-to-late fall, respectively, depending on the amount and seasonality of precipitation, the soil type and compaction, and the maturity of vegetation. The maximum storage in both lysimeters occurred in spring 2000 before plants became established. Because drainage also occurred at that time, water storage may have reached the maximum limit for each soil type: about 440 mm in Lysimeter 1 and 400 mm in

Lysimeter 2. The lower maximum storage limit for Lysimeter 2 as compared with Lysimeter 1 may be attributable to a lower porosity in the more compacted clay loam than in the less compacted loam. Once vegetation established during the dry years, the seasonal peak storage did not approach the limit in either lysimeter and no drainage occurred.

Seasonal low water-storage levels also differed between the two lysimeters. The difference is most likely attributable to differences in ET. During the 2000 growing season, before plants established, the seasonal low remained at about 280 mm; only about a 5-mm difference was observed between lysimeters. After plants became established, water storage in the less compacted loam (Lysimeter 1) dropped below 200 mm, about 30 mm below water storage in the compacted clay loam (Lysimeter 2). The water storage capacity of a soil layer can be calculated as the difference between the maximum storage limit and the lowest measured water storage level after the plant water potential reaches the wilting point. If this definition is used, the water storage capacity for the less compacted loam soil in Lysimeter 1 (about 250 mm) is more than 40% greater than the more compacted clay loam in Lysimeter 2 (about 175 mm).

Plant Abundance

The hydrologic performance of the Monticello cover relies, in part, on the establishment and resilience of a diverse plant community. Species composition, leaf area index (LAI), productivity, and percent cover were measured on the caisson lysimeters near the end of the 2002 and 2003 growing seasons. Species composition and percent cover were measured over the entire 7.3-m2 lysimeter surface. The lysimeter surface was divided into 50- by 100-cm quadrats delineated with string. A quadrat is an area of ground surface delimited for plant measurement. All plant species in each quadrat were recorded. We used an ocular point-intercept sampling method (Floyd and Anderson, 1982) to measure percent cover in each quadrat. LAI and productivity of green vegetation (current year's growth) were sampled in half of the quadrats by harvesting green leaf material and running the leaves through a Licor, Inc. LI-3100 Area Meter (www.licor.com). Green leaf material was harvested by hand or cut with shears, placed in paper bags, and processed soon after returning to the laboratory. Sagebrush green leaves were not removed because defoliation can stress or kill the plants.

Total percent cover for all plants growing in lysimeters, when averaged over years and lysimeters (37.1%, S.E.=0.6%, n = 4), was close to the minimum 40% cover criterion (Kastens and Waugh, 2002). However, as much as 20.6% cover or 56% relative cover consisted of species either not listed as a permissible or listed as noxious and non-noxious weeds (Table 2). Only about 16.5% of the cover consisted of permissible species, well below the requirement.

Total plant cover remained consistent between lysimeters and years (Figure 5). Green LAI, a better measure of the transpiration potential than percent cover, was significantly greater in 2002 on the less compacted loam (Lysimeter 1) than on the overly compacted clay loam (Lysimeter 2). Greater transpiration loss may partially explain the seasonally lower water storage values and consistently greater water storage capacity of the less compacted loam. As an apparent anomaly, productivity was highest on Lysimeter 2 in 2003, possibly attributable to the combination of a wet late summer, different species composition, and a later sampling date in 2003. Much of the high 2003 biomass on Lysimeter 2 is thick-stemmed alfalfa that re-greened following late summer rains.

OVERVIEW OF NATURAL ANALOGS OF LONG-TERM COVER PERFORMANCE

The performance of engineered covers will change in the long term as environmental conditions inevitably evolve in response to natural processes. Understanding how environmental conditions may change is crucial to designing, constructing, and maintaining long-term cover systems (Clarke et al., in press). Effective modeling and performance assessment requires scenarios based on both current and

Table 2. Plant species composition and percent cover.

Scientific Name[a]	Common Name[a]	% Cover
Permissible Species[b]		16.5
Grasses		15.1
Bromus inermis	Smooth brome	2.2
Pascopyrum smithii	Western wheatgrass	10.0
Thinopyrum intermedium	Intermediate wheatgrass	2.9
Forbs		1.4
Astragalus spp	Milk vetch	0.4
Sphaeralcea spp	Globemallow	*
Shrubs		1.0
Artemisia tridentata	Big sagebrush	0.7
Ericameria nauseosa	Rubber rabbitbrush	0.3
Non-Noxious Weed Species[b]		0.5
Kochia scoparia	Mexican fireweed	*
Salsola kali	Russian thistle	0.5
Not Listed as Permissible or Not Permissible[b]		20.1
Grasses		16.0
Achnatherum hymenoides	Indian ricegrass	0.3
Agropyron cristatum	Crested wheatgrass	1.1
Bromus tectorum	Cheatgrass	0.5
Elymus lanceolatus	Streambank wheatgrass	0.7
Elymus trachycaulus	Slender wheatgrass	2.8
Pseudoroegneria spicata	Bluebunch wheatgrass	3.1
Hesperostipa comata	Needle and thread	0.3
Unidentifiable perennial grasses		7.2
Forbs		4.1
Achillea millefolium	Common yarrow	*
Amaranthus blitoides	Mat amaranth	*
Chenopodium album	Lambsquarters	*
Linum perenne	Blue flax	2.6
Medicago sativa	Alfalfa	1.5
Taraxacum officinale	Common dandelion	*
Ground Surface		68.3
Soil		30.8
Rock		10.4
Litter		27.1

[a]Scientific and common names are consistent with the USDA Plants National Database.
[b]Plant categories are from revegetation acceptance criteria for the Monticello cover.

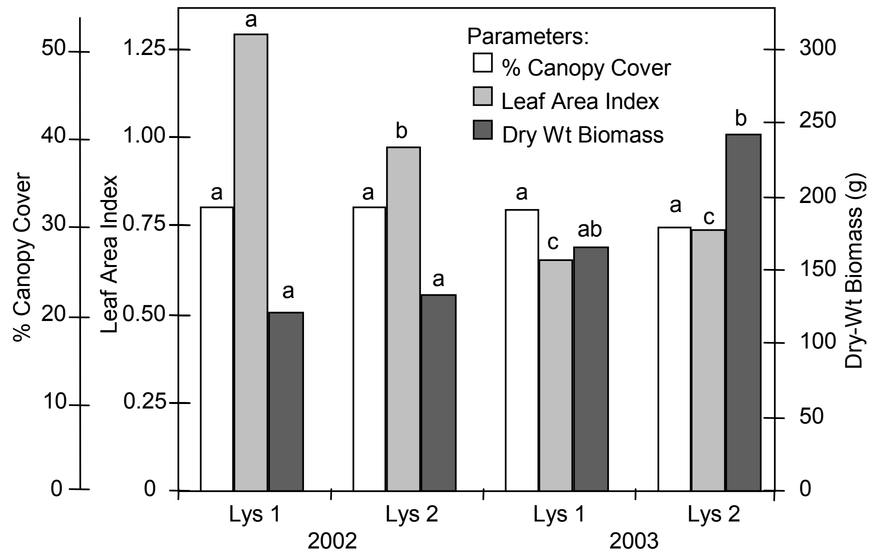

Figure 5. Percent cover, green LAI, and annual productivity comparing Lysimeters 1 and 2 in 2002 and 2003. Within-parameter bars with the same letter are not significantly different (P <0.05).

possible future environmental settings (Ho et al., 2002). Natural analog studies help identify and evaluate likely shifts in cover environments that cannot be predicted with model extrapolations of short-term field tests (Waugh et al. 1994). Natural analog information is needed (1) to engineer cover systems that mimic favorable natural systems, (2) to bound possible future conditions for input to predictive models and field tests, and (3) to provide clues about the possible evolution of engineered covers as a basis for monitoring leading indicators of change. Natural analogs also help demonstrate to the public that numerical predictions have real-world complements. DOE and its partners have collaborated on studies of natural and archaeological analogs to discern possible long-term changes in the environmental setting of engineered covers, including climate change, pedogenesis (soil development), and ecological succession (Waugh et al., 2003).

Climate data are required for design and performance evaluations of engineered covers (Ho et al., 2002). Evaluations may require projections of long-term extreme events and shifts in climate states over 100s and 1,000s of years, as well as annual and decadal variability in meteorological parameters. DOE and its partners have demonstrated methods based on global change models and paleoecological evidence to establish a first approximation of possible future climatic states at the Monticello site. A preliminary analysis of paleoclimate data yielded average annual temperature and precipitation ranges of 2 to 10 °C and 80 to 60 cm, respectively, corresponding to late glacial and mid-Holocene periods (Waugh and Petersen, 1995). Instrumental records for stations within the Four Corners Region were then used as a basis for selecting soil and vegetation analog sites that span a reasonable range of future climate states for Monticello (Waugh et al., 2003).

Pedogenic (soil development) processes will change soil physical and hydraulic properties that are fundamental to the performance of engineered covers. Pedogenesis includes processes such as (1) formation of macropores for preferential flow associated with root growth, animal holes, and soil structural development; (2) secondary mineralization, deposition, and illuviation of fines, colloids, soluble salts, and oxides that can alter water storage and movement; and (3) soil mixing caused by freeze-thaw activity, animal burrows, and the shrink-swell action of expansive clays (Chadwick and Graham, 2000). DOE and its partners have measured key soil physical and hydraulic properties in natural and archaeological soil profiles at climate analog sites to infer possible future pedogenic effects on the performance of the Monticello cover (Waugh et al., 2003).

Plant communities will establish and change on soil covers, whether intended or not, in response to climate, to soil development, and to disturbances such as fire, grazing, or noxious plant invasion. Changes in plant abundance, evapotranspiration rates, root penetration, and animal burrowing may alter the soil water balance and stability of a cover. DOE and its partners draw evidence of possible future ecological changes from successional chronosequences. For example, at the Lakeview, Oregon, disposal site, possible future responses of plant community composition and LAI to fire were evaluated using a nearby fire chronosequence. Possible vegetation responses to climate change scenarios were evaluated at regional global-change analog sites. LAI, as an index of plant transpiration, ranged from 0.15 to 1.28 for the fire chronosequence and from 0.43 to 1.62 for dry and wet climate analog sites.

CONCLUSIONS

The U.S. Department of Energy in Grand Junction, Colorado, has learned several lessons from monitoring, designing, and evaluating the long-term performance of engineered covers for uranium mill tailings disposal cells that could be of benefit to designers of the next generation of covers.

Early covers that rely on compacted soil layers (CSLs) to limit water movement into tailings may fall short of permeability targets. Many inadvertently created habitat for deep-rooted plants. Root intrusion and soil development in several covers has increased the saturated hydraulic conductivity (Ksat) several orders of magnitude above design targets. At the Shiprock, New Mexico site, a saturated CSL and a high Ksat indicate that more water than expected might be passing into the tailings. DOE may measure flux directly to assure that ongoing efforts to remediate ground water are not compromised by seeping of contaminants from the disposal cell. Saturated flow into tailings is likely occurring in the Burrell, Pennsylvania disposal cell. However, at Burrell, because of low contaminant concentrations in the disposal cell, a risk assessment indicates that root intrusion and increased saturated flow are not adversely impacting human health or the environment (Waugh et al., 1999).

Relatively low precipitation, high potential evapotranspiration (ET), and thick unsaturated soils favor long-term hydrologic isolation of buried waste at arid and semiarid sites. Alternative ET covers, such as the one designed for the Monticello, Utah, Superfund site, mimic this natural soil-water balance. The Monticello cover relies on a thick soil sponge layer overlying a sand-and-gravel capillary barrier to store precipitation while plants are dormant, and native vegetation to dry the sponge layer during the growing season. Lysimeters were constructed to match the range of as-built conditions in the Monticello cover. Results show that since 2000, about 0.1 mm of drainage occurred in both lysimeters during an average precipitation year and before they were planted, an amount well below the EPA target of <3.0 mm/yr. However, the cover with a less compacted loam topsoil had a 40% greater water storage capacity than the cover with overly compacted clay loam subsoil. The lesson learned is that seemingly subtle differences in soil types, sources, and compaction can result in salient differences in performance.

An objective for building alternative covers, given unprecedented longevity requirements, is to accommodate long-term ecological processes with the goal of sustaining performance with as little maintenance as possible. Investigations of natural analogs can provide insights as to how ecological processes may influence the performance of engineered covers, processes that cannot be addressed with short-term field tests or existing numerical models. Evidence from natural analogs can improve our understanding of (1) meteorological variability associated with possible long-term changes in climate; (2) vegetation responses to climate change and disturbances; (3) effects of vegetation dynamics on ET, soil permeability, soil erosion, and animal burrowing; and (4) effects of soil development processes on water storage, permeability, and site ecology.

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